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PERFORMANCE EVALUATION TESTS OF INSULATED PRESSURE VESSELS FOR VEHICULAR HYDROGEN STORAGE

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Insulated pressure vessels are cryogenic-capable pressure vessels that can be fueled with liquid hydrogen or ambient-temperature compressed hydrogen. This flexibility results in multiple advantages with respect to compressed hydrogen tanks or low-pressure liquid hydrogen tanks. Our work is directed at verifying that commercially available aluminum-lined, fiber-wrapped pressure vessels can be safely used to store liquid hydrogen. A series of tests have been conducted, and the results indicate that no significant vessel damage has resulted from cryogenic operation. Future activities include a demonstration project in which the insulated pressure vessels will be installed and tested on two vehicles. A draft standard will also be generated for certification of insulated pressure vessels.

1. Introduction

Hydrogen-fueled vehicles present features that make them serious candidates as alternatives to today's petroleum-powered vehicles. Hydrogen vehicles can use the advanced technology of electric vehicles to improve environmental quality and energy security, while providing the range, performance, and utility of today's gasoline vehicles.

Probably the most significant hurdle for hydrogen vehicles is storing sufficient hydrogen on board. Hydrogen storage choices can determine the refueling time, cost, and infrastructure requirements, as well as indirectly influence energy efficiency, vehicle fuel economy, performance, and utility. There are at least three viable technologies for storing hydrogen fuel on cars. These are compressed hydrogen gas (CH_2), metal hydride adsorption, and cryogenic liquid hydrogen (LH_2). Each of these has significant disadvantages.

Storage of 5 kg of hydrogen (equivalent in terms of energy to 19 liters; 5 gallons of gasoline) is considered necessary for a general-purpose vehicle, since it provides a 640-km (400-mile) range in a 34 km/liter (80 mpg) hybrid vehicle or fuel cell vehicle. Storing this hydrogen as CH_2 requires a volume so big that it is difficult to package in light-duty vehicles [1]. The external volume for a pressure vessel storing 5 kg of hydrogen at 24.8 MPa (3600 psi) is 320 liters (85 gal). Hydrides are heavy (300 kg for 5 kg of hydrogen [2]), resulting in a substantial reduction in vehicle fuel economy and performance.

Low-pressure LH_2 storage is light and compact, and has received significant attention due to its advantages for packaging [3]. Recent developments have resulted in improved safety [4,5], and fueling infrastructure [6]. Disadvantages of low-pressure LH_2 storage are the substantial amount of electricity required for liquefying the hydrogen [7]; the evaporation losses that may occur during fueling low-pressure LH_2 tanks [8]; and the evaporative losses that occur during periods of inactivity, due to heat transfer from the environment.

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An alternative is to store hydrogen in an insulated pressure vessel that has the capacity to operate at LH_2 temperature (20 K), and at high pressure (24.8 MPa; 3600 psi). This vessel has the flexibility of accepting LH_2 or CH_2 as a fuel. Filling the vessel with ambient-temperature CH_2 reduces the amount of hydrogen stored (and therefore the vehicle range) to about a third of its value with LH_2.

The fueling flexibility of insulated pressure vessels results in significant advantages. Insulated pressure vessels have similar packaging characteristics as liquid hydrogen tanks (low weight and volume), with reduced energy consumption for liquefaction. Energy requirements for hydrogen liquefaction are lower than for liquid hydrogen tanks because a car with an insulated pressure vessel can use, but does not require, cryogenic hydrogen fuel. A hybrid or fuel cell vehicle with 34 km/l (80 mpg) gasoline-equivalent fuel economy could be refueled with ambient-temperature CH_2 at 24.8 MPa (3600 psi) and achieve a 200 km range, suitable for the majority of trips. The additional energy, cost, and technological effort for cryogenic refueling need only be undertaken (and paid for) when the additional range is required for longer trips. With an insulated pressure vessel, vehicles can refuel most of the time with ambient-temperature hydrogen, using less energy, and most likely at lower ultimate cost than LH_2, but with the capability of having 3 times the range of room-temperature storage systems. Use of compressed hydrogen in all trips under 200 km (which represent 85% of all the distance traveled in the USA [9]), reduces the total energy consumption by 16% over the energy consumed by a vehicle that is always filled with LH_2.

Insulated pressure vessels also have much reduced evaporative losses compared to LH_2 tanks. This has been demonstrated in a previous work [10], which presents a thorough analysis of evaporative losses in cryogenic pressure vessels based on the first law of thermodynamics. Figure 1 illustrates some of the main results. This figure shows hydrogen losses during vehicle operation. The figure assumes that two vehicles are fitted with cryogenic hydrogen storage tanks with the same capacity (5 kg). One vehicle has a low-pressure (0.5 MPa; 70 psia maximum) conventional liquid hydrogen tank, and the other has an insulated pressure vessel. The vehicles are identical in every respect, except for the tanks. The vessels are filled to full capacity with liquid hydrogen, and then the vehicles are driven a fixed distance every day. When the fuel runs out, the amount of fuel burned by the engine and the amount of fuel lost to evaporation are calculated, and the results are shown in Figure 1. The figure shows total cumulative evaporative hydrogen losses out of a full tank as a function of the daily driving distance, for a high-efficiency vehicle (34 km/l or 80 mpg gasoline equivalent fuel economy). As expected, evaporative losses increase as the daily driving distance is reduced, because less driving results in a longer time for hydrogen evaporation. The figure shows that a low-pressure LH_2 tank loses hydrogen even when driven 100 km per day. Losses from a LH_2 tank grow rapidly as the daily driving distance drops. A vehicle driven 50 km per day (the average for the USA [9]) loses almost 1 kg (20%) of the fuel to evaporation. On the other hand, insulated pressure vessels lose hydrogen only for very short daily driving distances (less than 5 km/day). Most vehicles are driven considerably more than this distance, so that most vehicles equipped with an insulated pressure vessel would never lose any hydrogen to evaporation during operation.

Insulated pressure vessels have the additional advantage over low-pressure cryogenic tanks of being able to deliver high-pressure fuel, which can be used in direct injected engines without the need of a high-pressure pump, which would add significant cost to the fuel delivery system.

From an engineering and economic perspective, insulated pressure vessels strike a versatile balance between the cost and bulk of ambient-temperature CH_2 storage, and the energy efficiency, thermal insulation and evaporative losses of LH_2 storage. In summary, insulated pressure vessels offer flexibility and savings, both in terms of energy and cost. Compared to liquid hydrogen tanks, insulated pressure vessels will save 36% of the energy consumption (16% saved for avoiding fuel liquefaction and 20% saved in reduced evaporative losses). Compared to compressed hydrogen storage, insulated pressure vessels offer a 50% cost reduction for the manufacture of the pressure vessel, due to the smaller vessel size required.

Considering all the potential benefits of insulated pressure vessels, it is important to determine what type of pressure vessel could be operated at both high pressure and cryogenic temperature. Of the available pressure vessel technologies commonly used for vehicular storage of natural gas [11] it appears that aluminum-lined, composite-wrapped vessels have the most desirable combination of properties for this application (low weight and affordable price). However, commercially available aluminum-composite pressure vessels are not designed for low temperature applications.

This paper describes work in progress directed at evaluating the possibility of using commercially available aluminum-fiber pressure vessels at cryogenic temperatures and high pressures, as would be required for vehicular hydrogen storage in insulated pressure vessels. The paper gives a description of previous and future tests. The purpose of these tests is to demonstrate that no technical barriers exist that prevent the use of aluminum-fiber pressure vessels at cryogenic temperatures. As a future task, we are planning to generate a draft for a certification standard which will be submitted to the relevant administrative bodies (DOT, ISO) for their consideration and approval. Another planned activity is a demonstration project in which insulated pressure vessels will be installed and tested on a vehicle.

2. Pressure Vessel Tests

Pressure and Temperature Cycling: Pressure vessels have been cycled through 900 high-pressure cycles and 100 low-temperature cycles. The cycles are alternated, running 9 pressure cycles followed by a temperature cycle, and repeating this sequence 100 times. This test is expected to replicate what would happen if these vessels were used in a hydrogen-fueled car. Liquid nitrogen is used for low-temperature cycling and gaseous helium for high-pressure cycling. To accomplish the required testing, an experimental setup has been built inside a high-pressure cell. A schematic is shown in Figure 2. The valves shown in the schematic are controlled by computer, which allows the system to run with no supervision, resulting in fast cycling. An aramid-aluminum and a carbon fiber-aluminum pressure vessel have been cycled. The vessels have not failed during the test.

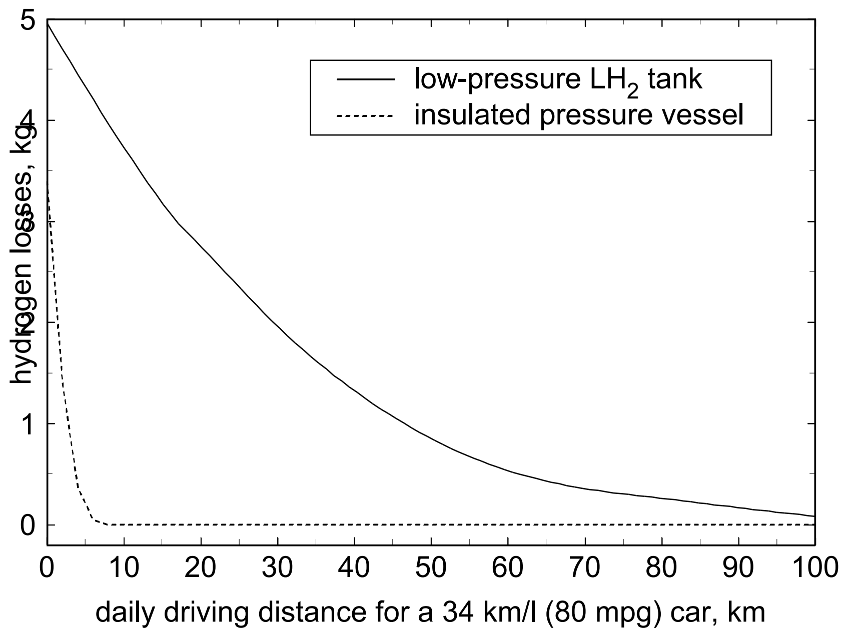

Figure 1. Cumulative hydrogen losses in kg as a function of daily driving distance, for vehicles with 17 km/liter (40 mpg); or 34 km/l (80 mpg) fuel economy, for three cryogenic hydrogen storage vessels.

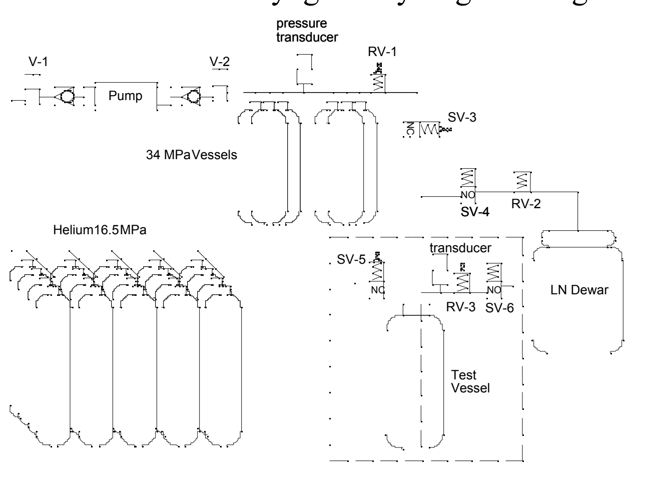

Figure 2. Schematic of the experimental setup for temperature and pressure cycling of pressure vessels.

Burst Test: The aramid-aluminum and the carbon fiber-aluminum pressure vessels were burst-tested after being cycled. The burst test was conducted according to the Code of Federal Regulations-Department of Transportation standards for pressure vessel certification [12]. Figure 3 shows the variation of pressure as a function of time for the aramid-aluminum vessel. Failure occurred by hoop mid cylinder separation, which is the preferred mode of failure. The burst pressure was 94.2 MPa (13.7 ksi), which is substantially higher than the minimum burst pressure of 72.4 MPa (10.5 ksi).

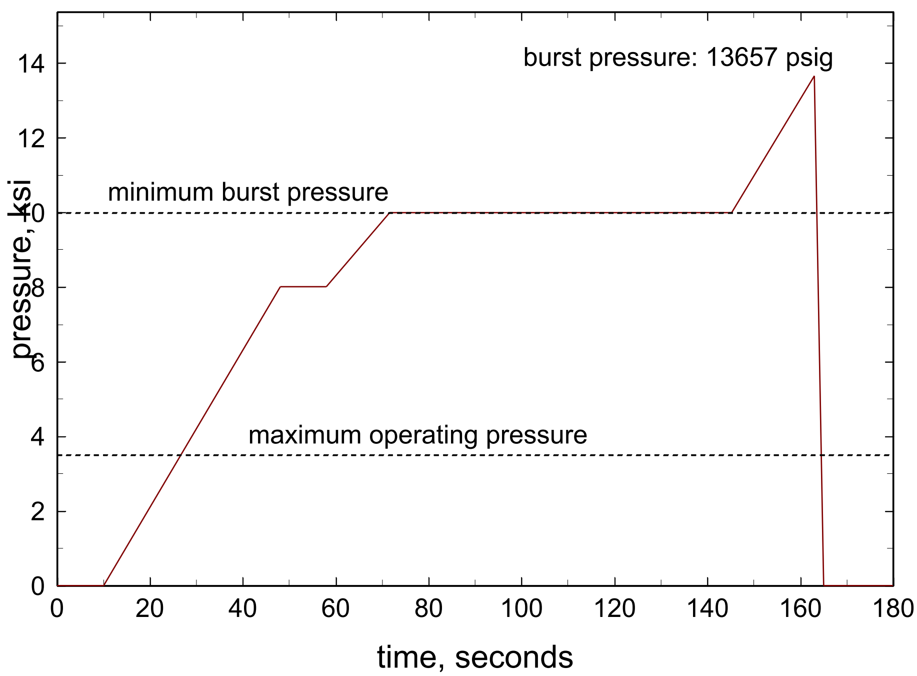

Figure 3. Pressure as a function of time during the burst test of the aluminum-lined, aramid-wrapped vessel. The burst pressure was 94.17 MPa (13657 psig).

Finite Element Analysis: Cyclic and burst testing of the pressure vessels has been complemented with a finite element analysis. The finite element analysis is done to determine whether low temperature operation can result in damage to the pressure vessel. Finite element analysis has been conducted with a commercial finite element package [13]. A mesh has been developed. This is an axisymmetric mesh with 1195 elements. Sensitivity of the results to mesh resolution was tested by building a second mesh with 4234 elements. Little difference was observed between the Von Mises stresses obtained with the two grids. Physical properties of fiber-epoxy laminae were obtained from available literature at ambient and cryogenic temperatures [14,15]. Lamina properties are then converted into properties of the composite matrix. This is done by using a computer program [16]. This program assumes that the matrix is a homogeneous, orthotropic material. The properties of the matrix are then used in the finite element thermal and stress analysis.

Finite element analysis of the pressure vessel considers the manufacture of the pressure vessel, starting from the curing process and continuing with the autofrettage cycle. The autofrettage is a process in which the vessel is subjected to a high internal pressure (45.5 Mpa, 6600 psi, in this case) to introduce a level of plastic deformation and pre-stress. After the autofrettage, the vessel is subjected to a series of low temperature and high-pressure cycles. These are identical to the sequence used for the cyclic test of the pressure vessel, consisting of a cryogenic cycle down to liquid nitrogen temperature followed by nine pressure cycles up to the design pressure.

Figure 4 shows the results of the analysis for plastic deformation in the aluminum at two points. These points are located at the center of the cylindrical part of the tank. The figure shows that the autofrettage cycle introduces a high level of plastic deformation. The first few cryogenic cycles also introduce some plastic deformation in the liner. However, successive cryogenic cycles introduce less and less plastic deformation, until the plastic deformation asymptotes to a value slightly higher than 4%. Further cycles do not increase the level of plastic deformation, and therefore the pressure vessel is not expected to fail due to repeated cryogenic cycles. This is in agreement with the cryogenic cyclic tests, in which the vessels were subjected to 100 cryogenic cycles with no damage or failure.

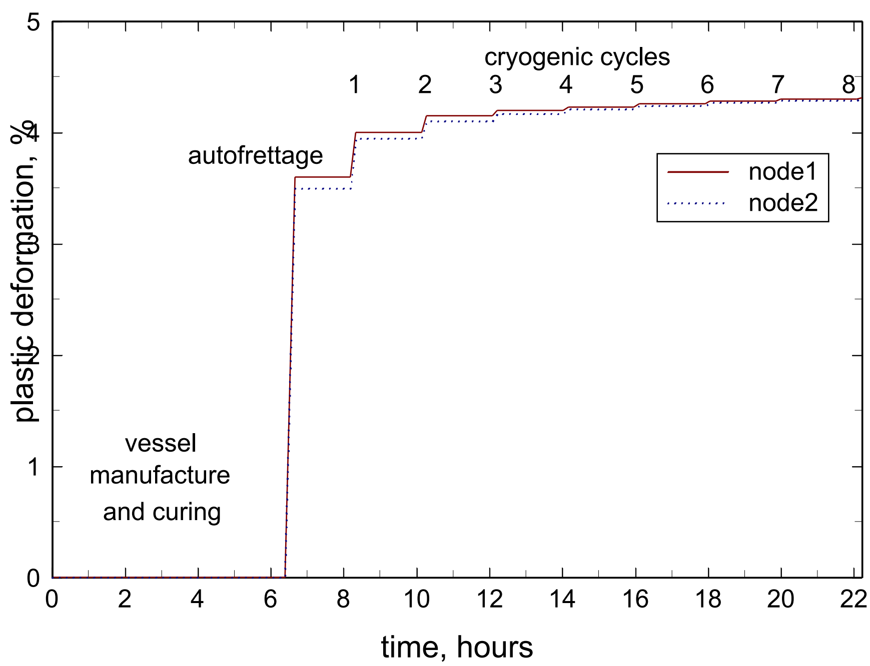

Figure 4. Plastic deformation obtained from the finite element analysis for two points in the liner. Nodes 1 and 2 are located at the center of the cylindrical part of the tank.

Insulation Design and Insulated Pressure Vessel Construction: Insulated pressure vessels have been designed to operate with multilayer vacuum superinsulation (MLVSI). MLVSI has a good thermal performance only under a high vacuum, at a pressure lower than 0.01 Pa (7.5×10^{-5} mm Hg [17]). Therefore, the use of MLVSI requires that an outer jacket be built around the vessel. Two designs for the insulation have been built: a first-generation design and a second-generation design. The first-generation vessel is a 1/5-scale vessel that stores about 1 kg of liquid hydrogen, and it is shown in Figure 5. This design has been built for cyclic testing and for DOT certification tests. The insulation design includes access for instrumentation for pressure, temperature and level, as well as safety devices to avoid a catastrophic failure in case the hydrogen leaks into the vacuum space. Five pressure vessels have been built according to the first-generation pressure vessel design. These vessels have been tested for compliance with DOT/ISO certification standards.

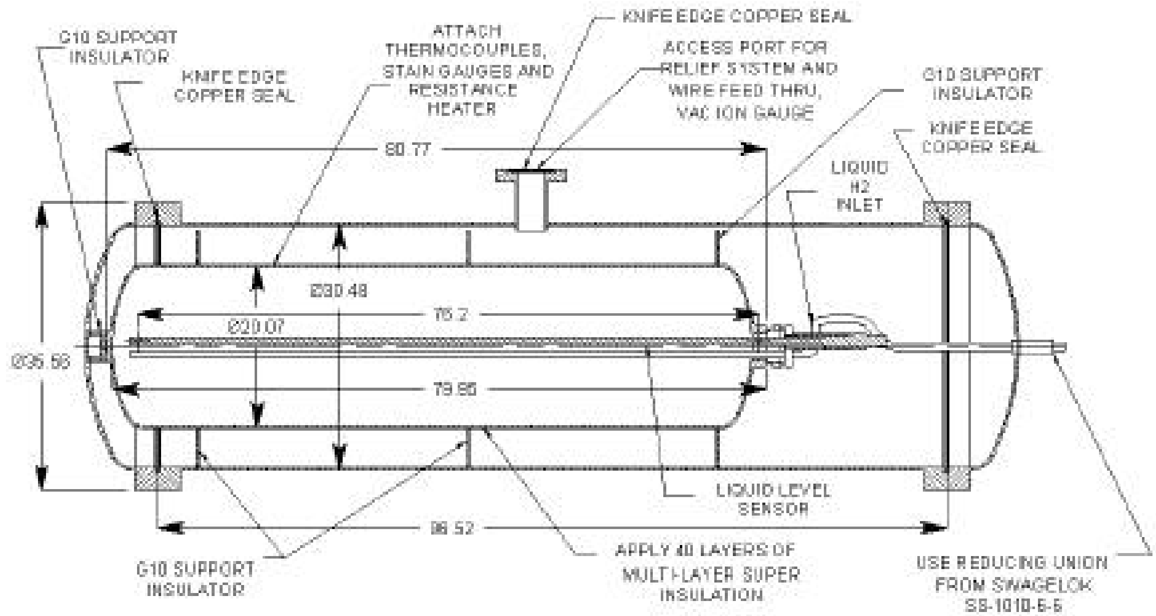

Figure 5. Insulation design for first-generation pressure vessel. The figure shows a vacuum space, for obtaining high thermal performance from the multilayer insulation, and instrumentation for pressure, temperature and level. Dimensions are given in cm.

The second-generation pressure vessel design is shown in Figure 6. This vessel can store about 6 kg of liquid hydrogen. This design includes a vapor shield to reduce evaporative losses in addition to the instrumentation and safety devices that exist in the first generation vessel. These vessels are currently being built. The second generation of pressure vessels will be used for DOT and SAE tests, and for incorporation into demonstration vehicles.

Liquid and Gaseous Hydrogen Testing: A first-generation insulated pressure vessel has been tested with liquid and gaseous hydrogen. The vessel was first shock-tested and leak-tested. The insulated pressure vessel was then transported to a remote facility for testing with liquid hydrogen. Testing involved filling the vessel with LH_2 to study the insulation performance, the performance of the sensors, and the problems involved with pumping the LH_2 into the vessel. This test is expected to replicate what would happen to the vessel during fueling and operation in an LH_2-fueled car. The test was conducted successfully. There was no damage to the vessel due to the low temperature operation, all the instrumentation operated properly at the low temperature, and there was no hydrogen ignition or explosions.

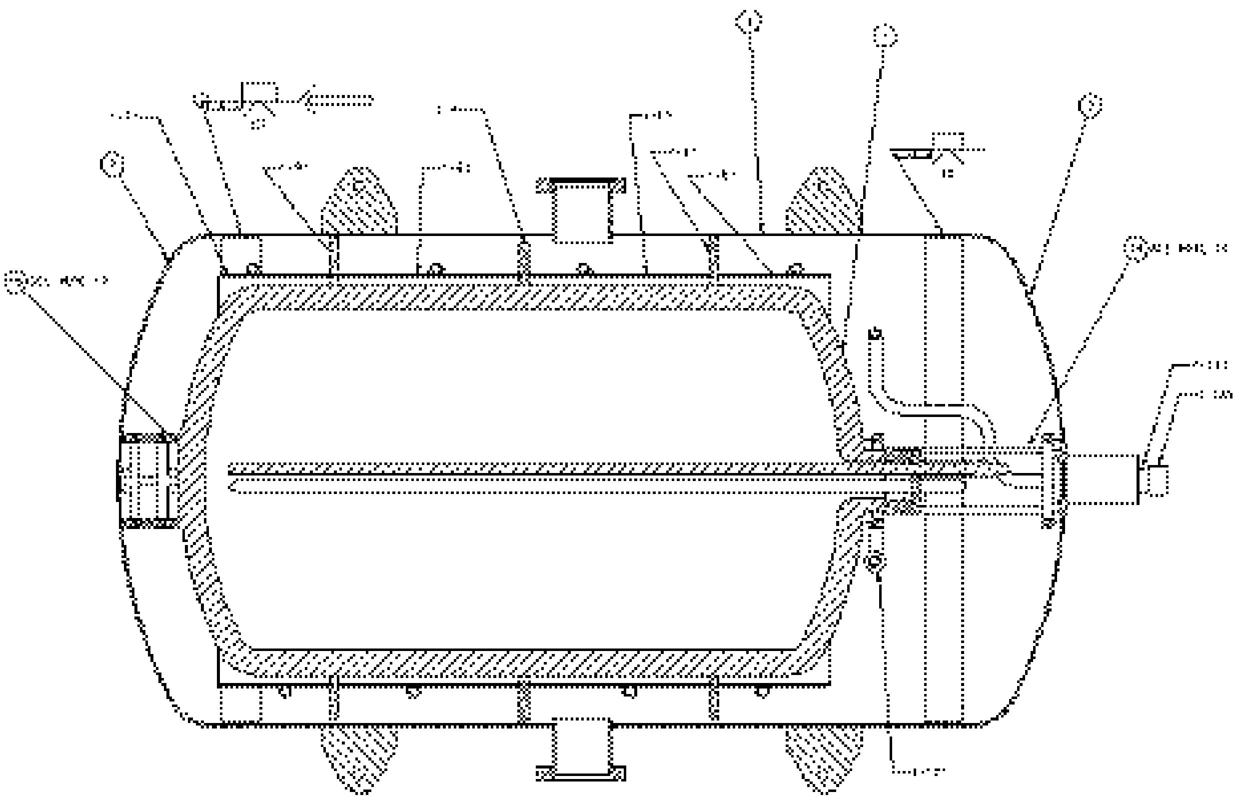

Figure 6. Insulation design for second-generation pressure vessel. The figure shows a vacuum space, for obtaining good performance from the multilayer insulation, instrumentation for pressure, temperature and level, and a vapor shield for reducing hydrogen evaporative losses.

DOT, ISO and SAE Certification Tests: Along with the cryogenic cyclic tests and the finite element analysis, insulated pressure vessels are being subjected to certification tests according to the standards set by the Department of Transportation (DOT), the International Standards Organization (ISO) and the Society of Automotive Engineers (SAE). A list of the tests that may be relevant to insulated pressure vessels has been generated. The selected tests are listed next. So far the first six tests have been successfully completed. The only remaining tests are the cryogenic drop and fire tests.

- Cycling, ambient temperature. 10000 cycles from less than 10% of the service pressure to the service pressure, 10 cycles per minute maximum [12]. Each test cylinder must withstand the cycling pressurization test without any evidence of visually observable damage, distortion, or leakage. This test has been successfully completed.

- Cycling, environmental. 10 cycles per minute maximum. 1) 5000 cycles from zero to service pressure with tank at $60^{o}C$ ($140^{o}F$) and air at ambient temperature and 95% humidity, 2) 5000 cycles from zero to service pressure with tank at $-51.1\,^{o}C$ (-

60°F) and air at ambient temperature, 3) 30 cycles from zero to service pressure, ambient conditions 4) burst test the cycled vessel [12]. Each test cylinder must withstand the cycling pressurization test without any evidence of visually observable damage, distortion, or leakage. This test has been successfully completed.

- Cycling, Thermal. 10 cycles per minute maximum. 1) 10 000 cycles from zero to service pressure at ambient temperature, 2) 20 thermal cycles with tank temperature varying from 93.3°C (200°F) to –51.1°C (-60°F) at service pressure, 3) burst test the cycled vessel [12]. Each test cylinder must withstand the cycling pressurization test without any evidence of visually observable damage, distortion, or leakage. This test has been successfully completed.

- Gunfire. Pressurize vessel with air or nitrogen to service pressure, and impact the vessel with a 0.30 caliber armor-piercing projectile with a speed of 853 m/s (2800 ft/s). The cylinder is positioned in such a way that the impact point is in the cylinder side wall at a 45° angle with respect to the longitudinal axis of the cylinder. The distance from the firing location to the cylinder may not exceed 45.7 meters (150 feet) [12]. The cylinder shall not fail by fragmentation. This test has been successfully completed.

- Bonfire. Pressurize cylinder with air or nitrogen to service pressure. Set pressure relief devices to discharge at 83% of the cylinder test pressure. The cylinder shall be exposed to fire until the gas is fully vented. The temperature measured on the surface tank exposed to the fire has to be between 850 and 900°C [12]. The venting of the gas must be predominantly through the pressure relief device. This test has been successfully completed.

- Drop Test from 3 m (10 ft). 1) The cylinder is dropped vertically onto the end, 2) the cylinder is dropped horizontally onto the side wall, 3) the cylinder is dropped onto a 3.8 x 0.48 cm (1 _ x 3/16 inch) piece of angle iron, 4) after the drops, the vessel is cycled over 1000 pressure cycles from 10% of service pressure to the service pressure, at 10 cycles per minute [12]. The cylinder then has to be burst tested; the burst pressure of this vessel has to be at least 90 % of the minimum burst pressure. This test has been successfully completed.

- Cryogenic drop tests from 10 m and 3 m. 1) Drop from 10 m. The drop test subjects a full-size vehicle fuel tank to a free-fall impact onto an unyielding surface from a height of 10 m. The fuel tank is released by firing one or more explosive cable cutters simultaneously. The fuel tank impacts the outer shell on the critical area as determined by the manufacturer. The fuel tank is filled with an equivalent full weight of liquid nitrogen saturated to at least 50% of the maximum allowable working pressure of the fuel tank. 2) Drop from 3 m. The drop test subjects a full-size vehicle fuel tank to a free-fall impact onto an unyielding surface from a height of 3 m. The fuel tank is released by firing one or more explosive cable cutters simultaneously. The fuel tank impacts the outer shell on the critical area as determined by the manufacturer. The fuel tank is filled with an equivalent full weight of liquid nitrogen saturated to at least 50% of the maximum allowable working pressure of the fuel tank [19]. There shall be no loss of product for a period of 1 hour after the drop other than relief valve operation and loss of vapor between the filler neck and the secondary relief valve in the case of a test involving the filler neck. Loss of vacuum, denting of the vessel, piping and piping protection, and damage to the support system are acceptable.

- Flame test with cryogenic fill. The tank should contain an equivalent full level of liquid nitrogen saturated at one half the maximum allowable working pressure (MAWP). The tank should be inverted and subjected to an external temperature of 538^{o}C (1000^{o}F) for 20 minutes without the vessel reaching relief pressure [19].

3. Technology Validation and Certification

All tests and analysis conducted to date indicate that insulated pressure vessels can safely be used to store cryogenic and ambient temperature compressed hydrogen for vehicular applications. The safety of insulated pressure vessels, along with their multiple advantages for vehicular hydrogen storage open the way for future commercialization of this technology. However, two remaining tasks have the potential of considerably advance the technology on its way to commercialization. These are field demonstration and vessel certification. To accomplish these tasks we have teamed up with a major pressure vessel manufacturer (Structural Composites Industries, SCI, Pomona, CA, USA), and a transit authority with a broad interest on alternative fuel vehicles and environmental projects (SunLine, Thousand Palms, CA, USA). SCI provides a direct path for future commercialization of this technology, while SunLine is the ideal place to conduct a demonstration of the technology.

For a demonstration of the technology we are planning to install an insulated pressure vessel in a Ford Ranger pickup truck driven by a hydrogen engine. Installation will include instrumentation of the tank with sensors for level, temperature and pressure. The vehicle will then be tested for a period of six months. The vehicle will be used as a regular vehicle of the SunLine fleet. The drivers and service personnel will thoroughly document fuel use, instrumentation performance, vehicle performance, refuelability issues, etc. We will ask for their comments and work on addressing these comments. Finally, we will write a comprehensive report on the experiences obtained during testing of the vehicles. The report will contain all of the users' comments and observations generated during testing. These comments will then be used to develop improved pressure vessel designs and continue down the path toward commercialization.

For the development of a procedure for vessel certification, we will start by studying existing pressure vessel standards (Department of Transportation, DOT; Society of Automotive Engineers, SAE; National Fire Protection Association, NFPA; American Society of Mechanical Engineers, ASME; etc.), to determine which of those can be applied to insulated pressure vessels. These will be incorporated into the proposed standards for insulated pressure vessels with little or no change.

Some existing standards cannot be applied to insulated pressure vessels. This is because they are technology-specific. For example, many standards that apply to cryogenic tanks require a specific type of weld and a specific material. These apply only to the specific technology being used for fuel storage (i.e. welded stainless steel tanks). For existing standards that cannot be applied to insulated pressure vessels, the standard will be studied in detail to determine its significance in terms of pressure vessel integrity. For standards that cannot be applied to insulated pressure vessels, we will identify an alternative standard that will satisfy a similar requirement in terms of vessel safety. Alternative standards will preferably be performance-based rather than technology specific. Alternative standards will be specified based on a detailed analysis of what the requirement implies for the integrity of the vessel. This detailed analysis will include numerical modeling and experimentation as needed.

Finally, we will write a report detailing the proposed standards. The proposed standards will be circulated to industry for comments. After incorporating the comments, the final standards will be submitted to the regulating agencies (SAE, DOT, and ISO) for their consideration.

4. Conclusions

Insulated pressure vessels are being developed as an alternative technology for storage of hydrogen in light-duty vehicles. Insulated pressure vessels can be fueled with either liquid hydrogen or compressed hydrogen. This flexibility results in advantages compared to conventional hydrogen storage technologies. Insulated pressure vessels are lighter than hydrides, more compact than ambient-temperature pressure vessels, and require less energy for liquefaction and have less evaporative losses than liquid hydrogen tanks.

For reduced cost and complexity it is desirable to use commercially available aluminum-fiber pressure vessels for insulated pressure vessels. However, commercially available pressure vessels are not designed for operation at cryogenic temperature. A series of tests has been carried out to verify that commercially available pressure vessels can be operated at cryogenic temperature with no performance losses. All analysis and experiments to date indicate that no significant damage has resulted. Future activities include a demonstration project in which the insulated pressure vessels will be installed and tested on two vehicles. A draft standard will also be generated for obtaining certification for insulated pressure vessels.

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Curriculum Vitae

Salvador M. Aceves received a Ph.D. at Oregon State University in 1989. He has been at Lawrence Livermore National Laboratory since 1993. He has worked on multiple projects in the area of applied thermodynamics and heat transfer, with a special focus on transportation applications. **Joel Martinez-Frias** received a Ph.D. from the University of Guanajuato in Mexico. He has been at LLNL since 1998. He is currently involved in the analysis of power generation systems: solid oxide fuel cells and gas turbines. **Francisco Espinosa-Loza** has been at LLNL since 2001. He has been working on finite element analysis of insulated pressure vessels and gas combustors for high temperature steam generators.